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Observed Relationships Between Lunar Tidal Cycles and Formation of Hurricanes and Tropical Storms[1]

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ABSTRACT—To examine the hypothesis of a worldwide relation between some lunar periods and tropical disturbances, we collected first-formation dates for 1,013 hurricanes and typhoons and 2,418 tropical storms in both hemispheres. Using the superposed epoch method, we found a lunar synodic cycle (29.53 days) in North Atlantic hurricane and northwest Pacific typhoon formation dates. About 20 percent more hurricanes and typhoons formed near new and full moon than near the quarters during a 78-yr period, showing a stronger peak at new moon than at full moon. Statistically, the existence of an effect dependent on the lunar synodic cycle is supported by a significance level of 7 percent on unsmoothed data from an analysis of variance for categorical data.

During the same 78 yr, North Atlantic tropical storms that did not later become hurricanes tended to form near the lunar quarters. Several other categories of tropical storms were not clearly related to the synodic month. Severe tropical storms in two portions of the Indian Ocean over 75 yr formed more often several days after syzygy and quadrature, but this and other severe tropical storm results lack definition, probably due to poor data.

Theoretical calculations of the lunar-solar gravitational tide showed that the anomalistic lunar cycle affects only the amplitude and not the timing of extrema. No marked anomalistic or latitude components in hurricane formation were found.

1. INTRODUCTION AND BACKGROUND

A comprehensive, objective, and quantitative study of the formation of hurricanes and tropical storms related to lunar gravitational tidal periods is overdue. Several recent studies of the possible effect of lunar cycles on various meteorological phenomena have been made by Brier (1968), Brier and Simpson (1969), and Lethbridge (1970). They show possible lunar cycles ranging in time and space scales from that of the zonal index over many years to that of 6-hr surface pressure variations. Millás (1928) found a 29.5-day cycle in Atlantic tropical cyclone development based on historical data available at the time. More recently, Smiley (1954) and Jordan and Smiley (1955) discussed some aspects of the hypotheses relating tidal forces to seasonal frequency in hurricane development. In the direct predecessor of our paper, Bradley (1964) showed that North Atlantic hurricanes between 1899 and 1958 followed a 29.53-day synodic month variation wherein more storms formed near the time of syzygy (new and full moon) than at any other time of the lunar month. He also showed an anomalistic component in storm formation. Visvanathan (1966) showed that depressions (winds up to 33 kt) in the Bay of Bengal and Arabian Sea formed more often near first quarter than at other times of the lunar month. Visvanathan suggests that, if this cycle is indeed caused by an extraterrestrial effect, data for the entire globe should be considered. Our study will reconsider the possible lunar effects on observed storm formation by investigating all available storm data.

Some background information concerning the lunar-solar gravitational tide should be provided. The tide is constantly changing as a consequence of the orbital motions of the disturbing bodies and the diurnal rotation of the earth. Doodson (1921) and Rauschelbach (1924) have given a full development of the tidal potential by expanding a series of simple sine-cosine functions with constant amplitude and period. The complete list of all components includes approximately 390 periods of which 100 are long period (ranging from 1 day to 17 yr), 160 are diurnal, 115 are semidiurnal, and 14 are one-third diurnal terms. Defant (1961) lists 19 principal components of which seven are used in "actual" practice in determining ocean tides. Schureman (1941) describes in detail the methods used for prediction of ocean tides in specific locations.

The quality of the data prevented study of the main diurnal and semidiurnal components. Hence, our analysis permits no direct statements that would distinguish any lunar (or solar) cycle of less than 1 day to be more important than another in relation to storm formation. Of the 100 long period components (of 1 day or more), there are three major periods on the order of a month that affect the phase and/or amplitude of the gravitational tide: (1) the synodic month (29.53 days) where the tide has maxima at new and full moon and minima at first and last quarter, (2) the anomalistic month (27.55 days) where the tide is a maximum at perigee and a minimum at apogee, and (3)

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HURRICANES AND TYPHOONS	SEVERE TROPICAL STORMS	TROPICAL STORMS
NORTH ATLANTIC O. 321	BAY OF BENGAL AND ARABIAN SEA 144	ALL TROPICAL STORMS (SOME BECAME HURRICANES)
N.W. PACIFIC O. 692	S.W. INDIAN OCEAN 229	
1013	373	N.E. PACIFIC O. 195
		S.W. PACIFIC O. 148
		343
T.S. - A HURRICANE OR TYPHOON	T.S. - A SEVERE STORM LATER	T.S. RELATED TO HURRICANES
NORTH ATLANTIC O. 321	BAY OF BENGAL AND ARABIAN SEA 144	N. ATLANTIC AND N.W. PACIFIC 1187
N.W. PACIFIC O. 314		
635		
T.S. - NO HURRICANE OR TYPHOON	T.S. - NO SEVERE STORM LATER	T.S. RELATED TO SEVERE T.S.
NORTH ATLANTIC O. 229	BAY OF BENGAL AND ARABIAN SEA 244	BAY OF BENGAL AND S.W. INDIAN O. 515
N.W. PACIFIC O. 323	S.W. INDIAN O. 127	
552	371	TOTAL TROPICAL STORMS: 2045

FIGURE 1.—Summary of number and location of all tropical storms [wind speed (V) > 33 kt], severe tropical storms ($V > 47$ kt), and hurricanes and typhoons ($V > 63$ kt) whose formation dates were analyzed for possible lunar tidal components.

the nodical month (27.21 days) where the tide is a maximum when the moon crosses the plane of the ecliptic.

It should be recognized that lunar tidal features constitute only an additional factor among many more significant conditions that lead to storm development. We visualize that the lunar tidal relationship to storm formation, as in the case of the lunar-rainfall relations reported by Brier (1965), derives only from enhancement of pre-existing meteorological disturbances by the lunar tidal forces in the atmosphere.

2. DATA

Historical storm data that can be analyzed for the presence of several lunar periods are of fundamental importance to this study. Thus, available data have been screened using the guideline that storm dates should be easily derived from simple inspection of standard sources. Many of these sources have been carefully listed by Gray (1968). Our principal requirement was that the data publication must indicate the dates when tropical cyclones attained either tropical storm or hurricane intensity. Figure 1 shows the location, number, and intensity of all disturbances used in our study. The data sample will not grow or improve considerably for many years.

Hurricanes and Corresponding Tropical Storm Data

Storm formation dates in the North Atlantic and northwest Pacific Oceans are probably the best documented anywhere in the world. This statement has some significance later because we will compare the less clear results from other oceans with the fairly consistent patterns from these two oceans. Cry (1965) has listed all storm dates from 1871 to 1963 for the North Atlantic. We used the annual hurricane summaries (Dunn and Staff 1965, Sugg 1966, 1967, Sugg and Pelissier 1968) for storms occurring after 1963. From these sources, we found the formation dates of 321 hurricanes between 1899 and 1967 and their corresponding earlier tropical storm formation dates. An additional 229 tropical storms listed during these same years did not later become hurricanes. Tracks were used simply by taking the first date (all times converted to GMT) when a depression became a tropical storm (maximum wind speed, V, greater than 33 kt) or a tropical storm reached hurricane force ($V>63$ kt). According to the data available for the earlier years, some tropical storms were full-blown hurricanes when discovered; their tracks were accepted literally to avoid possible subjective bias.

For the northwest Pacific Ocean (i.e., Pacific in Northern Hemisphere westward of the International Date Line), the principal source for the period 1891–1953 is the Hong Kong storm list by Chin (1958). In this reference, any track that begins with a dashed line indicates an uncertain track and intensity; those storms were omitted from our list. We also discarded any storm that began at the edge of the map area. The greatest remaining error source was our inability to determine the first-formation date for storms that were already at typhoon stage when discovered. The first-tropical storm dates were also provided by Chin (1958), but we did not use tropical storm formation dates when they were the same as typhoon formation dates. For the period 1958–68, the dates were found in the *Annual Typhoon Reports*,[3] both for typhoon formation and their earlier tropical storm dates. (These are better known than in earlier years.) This leaves a break in the literature from 1954 to 1957. This gap was kindly filled by the U.S. Navy Fleet Weather Central/Joint Typhoon Warning Center (1968). They provided first dates when typhoon stage was reached, based on their reconnaissance files. Their "first located" date was taken to be near the tropical storm formation time. The Warning Center also provided dates from 1949 to 1953 that were used in conjunction with Chin's (1958) data for those years. Figure 1 shows that we found 692 acceptable ty-

[3] Prepared by U.S. Navy Fleet Weather Central/Joint Typhoon Warning Center, Guam, Mariana Islands

phoon formation dates in the northwest Pacific between 1891 and 1968 and 314 of their corresponding first-tropical storm dates. We listed another 323 tropical storms that formed during these years but did not subsequently develop into typhoons.

Inadequate data in other parts of the world prevented any meaningful analysis of other tropical cyclones reaching hurricane intensity; therefore, we will consider only the 1,013 hurricanes and typhoons from the North Atlantic and northwest Pacific as our sample.

Severe Storms and Corresponding Tropical Storm Data

Numerous tropical storms develop in the north Indian Ocean (Bay of Bengal and Arabian Sea) and southwest Indian Ocean, but a relatively small percentage of them reach hurricane intensity. Cry (1965) distinguishes between two types of tropical storms, the moderate tropical storm (34–47 kt) and the severe tropical storm (48–63 kt). The Institute of Tropical Meteorology, Poona, India (1964), has published tracks for north Indian Ocean storms according to this breakdown, which differs from methods used in the North Atlantic and northwest Pacific. From 1891 to 1960, these tracks provided the first-formation dates of 144 severe tropical storms (termed "severe storms"). Many of these may have reached hurricane stage, but this information was not recorded. Corresponding earlier moderate tropical storm dates for these 144 severe storms were also available; however, more than half of them are the same for both stages. Also listed are 244 moderate storms that never developed further. Chaussard and Laplace (1964) give similar information about severe tropical storms in the southwest Indian Ocean (west of 80°E to the African Coast) for the period 1911–61. We accepted their listed first dates for severe tropical storms ("cyclone tropical"). The corresponding moderate tropical storm dates were not used in this rather data-poor region. Annual Mauritius Observatory Reports [4] provided additional severe tropical storm data for the period 1961–66; a total of 229 southwest Indian Ocean severe storm dates were obtained. No moderate storm dates were extracted for these recent years either. For the 127 nonintensifying moderate tropical storms, we used the first listed day for the "dépression tropicale."

The total number of accepted severe tropical storm dates (fig. 1) in the southwest Indian Ocean, Bay of Bengal, and Arabian Sea is 373; we used the earlier moderate tropical storm dates for 144 of these. Another 371 nonintensifying moderate storms were found.

Other Tropical Storm Data

Observations of tropical storms in other oceanic regions are also recorded. Recent improvements in observational techniques are generally credited with a sizable increase in the number of storms and hurricanes observed in the northeast Pacific; that is, the region west of Baja California and Mexico (Sadler 1964). For the early years, we used the first dates given by Hurd (1929) for some tropical storms from 1895 to 1928. Rosendal (1962) reviewed all known storms for the year 1939 and for the period 1947–61; again we used the first date of appearance as the first-tropical storm date, although information in these earlier years was quite inaccurate. For 1962–67, the dates were obtained from annual lists by Benkman (1963), Wilgus (1964), McGurrin (1965), Baum (1966, 1967), and Gustafson (1968). From these sources, we have found 195 northeast Pacific first-tropical storm dates from 1895 to 1967, mostly in recent years. Some of these later became hurricanes but were not included in the analyses.

Tropical storms and hurricanes are also observed in the southwest Pacific (south of the Equator from about 140°E eastward). Storms observed in this region during the 1940–47 period are listed by Hutchings (1953). The first date given for each storm on the list was taken as the tropical storm formation date. The data for 1948–61 were obtained from Giovanelli (1963); we used the "date de debut" for tropical storms. For storms between 1962 and 1966, the first dates of class 1 storms (over 33 kt with gales extending outward more than 100 mi) given in yearly summaries from the Australian Bureau of Meteorology [5] were used as tropical storm dates; the smaller sized class 2 storms were not included. A total of 148 tropical storms in the southwest Pacific were listed.

3. ANALYSIS TECHNIQUES

The storm formation dates were analyzed with the method of superposed epoch described by Panofsky and Brier (1958). For example, to find the relations between storm formation and the lunar synodic month, we used the procedures in figure 2. For the synodic lunar month, which lasts 29.53 days, the month was divided into 100 equal classes called synodic decimals. New moon is placed at decimal 00 and full moon at 50, and the quarters are at 25 and 75. Then we overlapped the two halves from 00 to 49 and 50 to 99, ignoring the small differences between the maximum monthly lunar tides at full and new moon and between the two quarters (collectively termed quadrature). The synodic decimal corresponding to each storm development date was taken from the ephemeris by Carpenter (1962), and the frequency of storm formation for each synodic decimal was tabulated. Some storm formation dates were listed at specific GMT hours, but due to the nature of the data, the synodic decimal for noon GMT was considered adequate. Then a 13-unit smoothing, which is a 3.85-day centered running mean (i.e., the storm date $\pm 1\frac{1}{2}$ days), was applied to this distribution of frequencies. This procedure smoothed out smaller scale variations due to the uncertainties in the true storm-formation dates. Bradley (1964) used the same smoothing technique.

The anomalistic period of the moon is the cycle from the point of its orbit closest to the earth (perigee) through

[4] Annual Reports of the Director of the Royal Alfred Observatory, Port Louis, Mauritius

[5] Yearly summaries of tropical cyclones in the northeastern and northwestern Australian regions were issued by the Director of Meteorology, Australian Bureau of Meteorology, Melbourne.

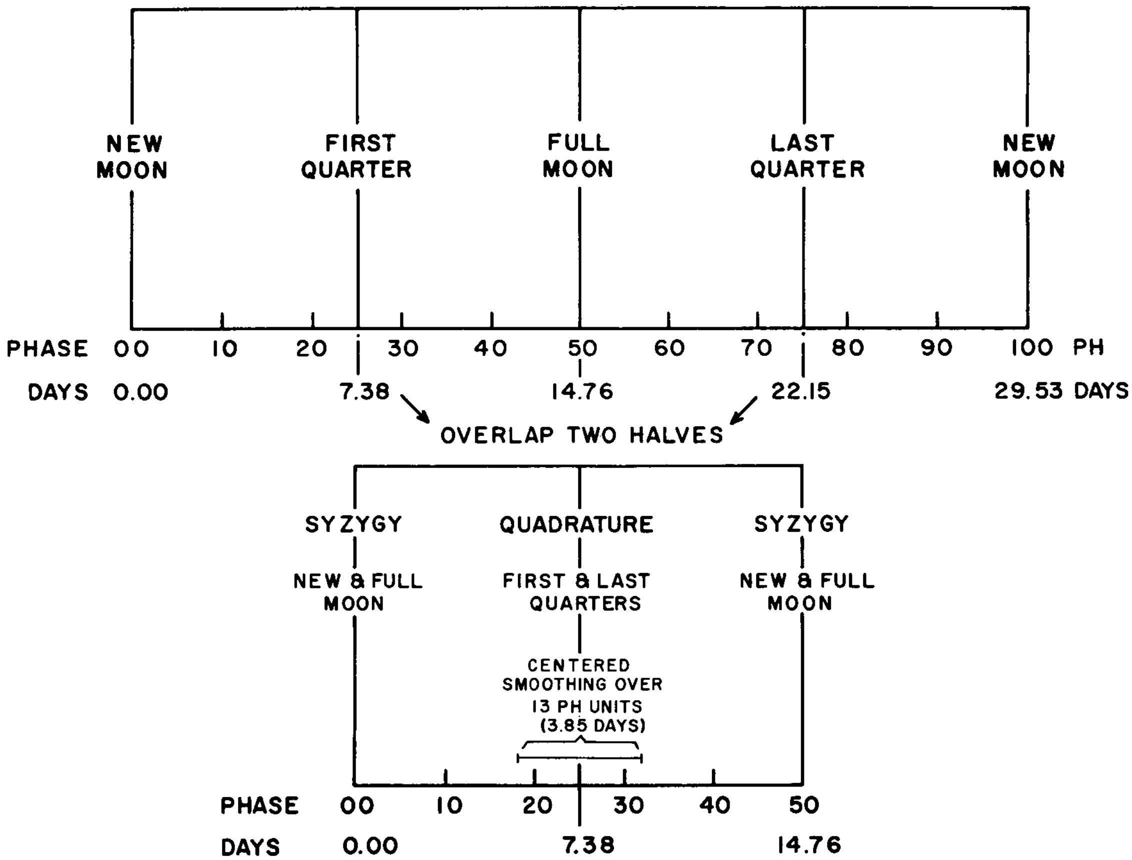

FIGURE 2.—Explanation of the superposed epoch procedure of analyzing the relation between storm formation and the lunar synodic month.

the farthest point (apogee) to perigee again. This anomalistic period lasts 27.55 days, slightly less than the synodic period of 29.53 days. The superposed epoch technique was also used for the anomalistic periodicity; however, reference was made to days before and after new or full moon rather than a synodic decimal because the moon moves faster during some parts of the anomalistic month than during other parts. This will be explained more later. Overlapping is not possible with the anomalistic cycle because there is only one maximum and one minimum per period.

Harmonic analyses of the data were also made. If the lunar tidal effect had a maximum effect at syzygy (when the moon and sun act on the earth together) and a minimum effect at quadrature (when the moon and sun act on the earth at right angles), the data would be described by the first harmonic, a sine curve with the peak centered at decimal 00. If storm formation dates varied exactly like this sine curve, 100 percent of the variance inherent in the data would be explained. The second harmonic has two cycles during the same time period, with peaks at both syzygy and quadrature. For a sample with data at 50 points as we have here, there are known to be 25 possible harmonics. Each harmonic would then account for 4 percent of the total variance by chance. However, the 13-unit moving average damps out higher harmonics so that probabilities greater than 4 percent result for the lower harmonics. This symmetric filter, nevertheless, affects only the magnitude and not the phase. For the first harmonic, the variance is the square of the correlation coefficient between smoothed storm formation frequencies and a cycle with a period of the half-synodic month.

4. RELATIONSHIPS BETWEEN STORM FORMATION AND THE LUNAR SYNODIC MONTH

The previous two sections have explained how the data were extracted and analyzed; now we concentrate on the results themselves.

Hurricanes and Corresponding Tropical Storm Results

In only the North Atlantic and northwest Pacific Oceans were data adequate to study hurricane development (sec. 2). Hurricane and typhoon formation frequency data are presented by figures 3 and 4; the 13-unit centered running sum (fig. 2 and sec. 3) along the ordinate is plotted against the overlapped synodic month along the abscissa. North Atlantic hurricane formation frequency is shown in the upper half of figure 3 and northwest Pacific typhoon formation frequency is in the lower half. Note that, for the upper panel of the figure, the ordinate scale ranges from 60 to 100 and applies to 321 hurricanes that occurred between 1899 and 1967 in the North Atlantic; the lower scale along the ordinate varies from 150 to 200 and applies to 692 typhoons that formed in the northwest Pacific between 1891 and 1968.

For the North Atlantic, there is a broad maximum in storm formation near syzygy and a minimum shortly

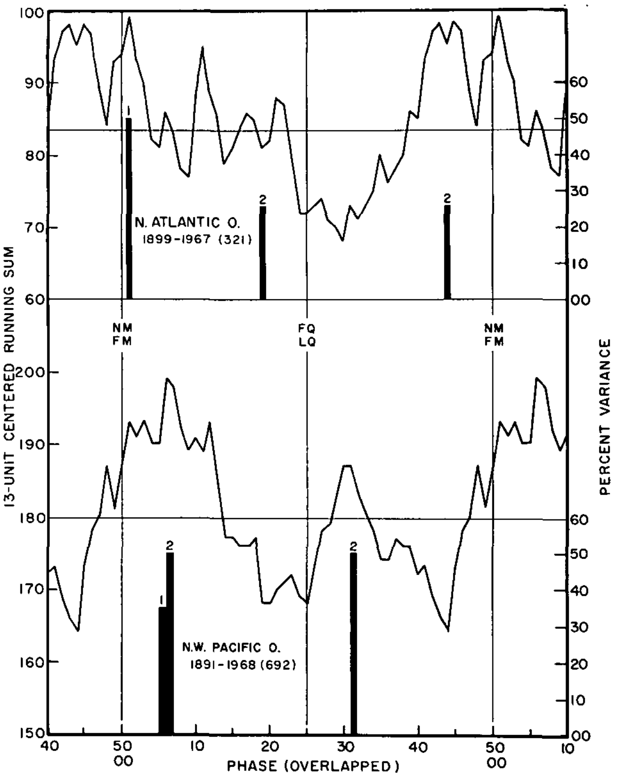

FIGURE 3.—Frequency of hurricane formation in the North Atlantic and typhoon formation in the northwest Pacific plotted as 13-unit centered running sums. First and last halves of the month are overlapped so that new and full moon (NM and FM) are at synodic decimals 50 and 00, and first and last quarters (FQ and LQ) are at decimal 25. Horizontal lines represent means of the 50 categories.

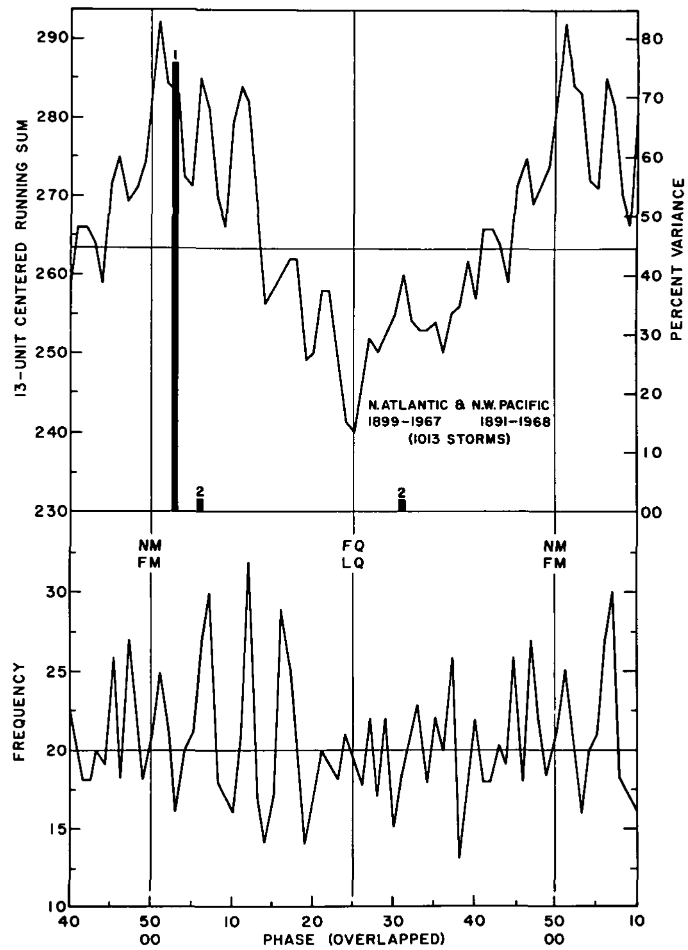

FIGURE 4.—Upper panel shows 13-unit smoothed formation frequencies for the same hurricanes and typhoons in the North Atlantic and northwest Pacific Oceans as in figure 3, explanation as in figure 3. Lower panel shows identical data in terms of overlapped frequencies but without smoothing.

after quadrature. In comparison, Bradley (1964) studied the 269 North Atlantic hurricanes that formed between 1899 and 1958 and found a more distinct maximum at syzygy and a minimum in frequency just past quadrature. We have been able to reproduce his result exactly for the same 269 hurricanes (not shown), which comprise a subset of the 321 storms in figure 3. Thus, the additional 8 yr of data only spread out the maximum shown by Bradley. The first harmonic for these 321 North Atlantic storms is centered at the synodic decimal 01 (see vertical bar with "1" on top) and accounts for 51 percent of the variance (see scale on right); while the second harmonic (bars with "2" on top) accounts for 26 percent of the variance with maxima at the time of synodic decimals 19 and 44.

The lower panel of figure 3 shows that in the northwest Pacific the maximum formation frequency of 692 typhoons is distinctly present about 2 days after syzygy. The first harmonic accounts for 35 percent of the variance and is centered at decimal 06. The second harmonic of 50 percent has maxima at synodic decimals 06 and 31. The second harmonic is greater than the first due to a peak in formation frequency just after quadrature, a peak that is not accountable in terms of any features of the synodic cycle.

Combining the hurricane formation dates in both of these oceans gives a sample of 1,013 storms and results in the curve shown by upper half of figure 4. We can clearly see a single maximum near syzygy and an equally strong minimum at quadrature; this is parallel to the effect of the lunar gravitational tide hypothesized in section 3. The first harmonic, centered at decimal 03, accounts for 76 percent of the variance after smoothing is performed, which results in a correlation coefficient of 0.87. This result would seem to indicate that a large number of reasonably accurate storm dates are needed to show this relatively minor lunar effect. Figure 4 shows a modulation of the running mean between syzygy and quadrature of about 20 percent.

The curve in the lower panel of figure 4 is from the same data, but without smoothing or running means. Craddock (1967) emphasized that unsmoothed data should also be published to allow readers to form their own opinions of the scatter in the original observations and the extent to which features claimed as significant are merely the result of smoothing. We see that the sine curve character of the smoothed frequencies is lost. However, more high frequencies of storm formation occur between decimals 45 and 16 while other decimals have near- or below-average frequencies of formation. Because most storm dates are available only to the nearest day and may be incorrect by 1 day either way, it is not unreasonable that some smoothing should be applied in this case, despite the possible misleading results of running mean techniques that Deacon (1966) indicated. Note that, even though 1,013 storms have been included, an average of only 20 storms belongs to each decimal category before overlapping is performed. The unsmoothed plot suggests that the peak in the smoothed result could be shifted to the right by 1 or 2 days.

We pause here to discuss the results of statistical analyses performed only on this set of 1,013 hurricanes and typhoons. A two-way analysis of variance was made on the unsmoothed data over the half-synodic month in the lower half of figure 4 to test for the contrast between storm formation at syzygy and quadrature. This analysis is similar to, but not the same as, the Bartels test (Bartels and Johnson 1940) of probability. Several assumptions must be made about the sample; independence and equal variance among the storm dates are not a serious problem. The F-test is rather robust to the departures from normality exhibited by the data. The analysis considered each year as an independent trial and compared each year's distribution of storm dates with a cosine curve having a peak at syzygy and a trough at quadrature. Results of the F-test showed a significance level of 10 percent for all years without transforming the data. Upon a transformation of the same storm dates with $Y=\sqrt{X+0.5}$, we find a significance level of 7 percent. Undoubtedly, there is considerable high-frequency noise in this sample; we should note again that this was performed on unsmoothed data. We further subdivided the storm dates into three periods: from 1891 to 1916, 1917 to 1942, and 1943 to 1968. No significant differences were found between the synodic cycle of storm formation for these subsets and for the entire 78-yr period. This indicates that the significance level result is independent of time. A major effort should be made to solve the very difficult problem of statistically analyzing data plotted with the superposed epoch method. We hope to instigate such a study in the near future. However, these storm dates would not appear to be as appropriate a vehicle for refining statistical techniques as would other atmospheric variables. Although not significant at the traditional level of 5 percent, the results of the analysis of variance of hurricane and typhoon data certainly point to some relationship with the lunar synodic cycle.

A periodicity has been suggested in hurricane development. What about earlier stages of the hurricanes and typhoons? Did they reach tropical storm intensity such that the cycles in figures 3 and 4 are simply shifted to the left by 2 or 3 days? Also, is there a difference between these tropical storms and those from which no hurricane developed later? The lower panel of figure 5 applies to tropical storm formation dates that correspond to the earlier stage of the same 321 North Atlantic hurricanes in figure 3. There is only a slight tendency for these tropical storms to have formed more often several days before and after syzygy. The first harmonic is small and the second harmonic of 38 percent has maxima at two other times during the synodic half month. The upper panel of figure 5 shows, however, a different behavior for the 229 tropical storms

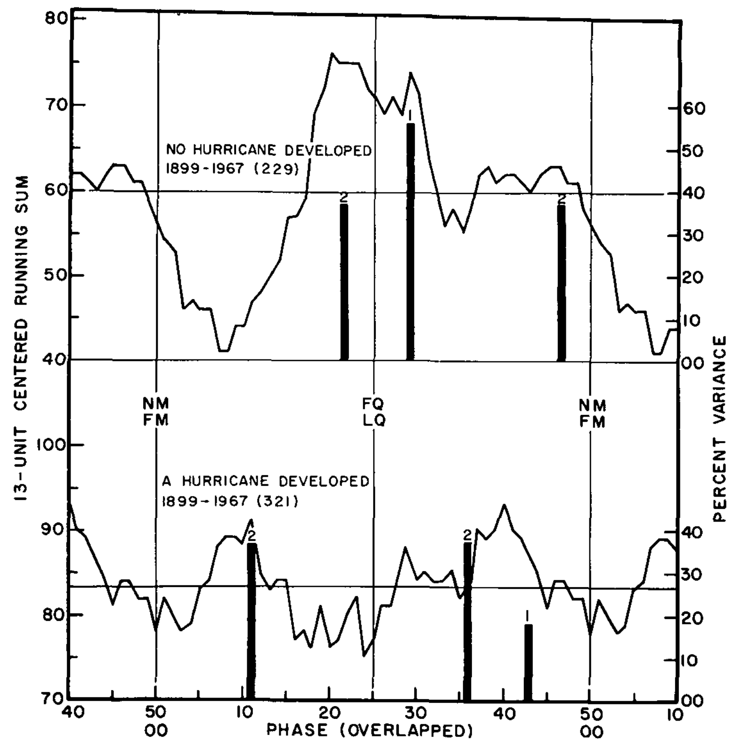

FIGURE 5.—Formation dates for North Atlantic tropical storms that did not become hurricanes (upper panel) and those that eventually did so (lower panel). Explanation is the same as for figure 3.

that formed between 1899 and 1967, but never reached hurricane intensity. These nondeveloping tropical storms formed much more often near quadrature than near syzygy. Here, 56 percent of the variance is accounted for by the first harmonic, centered at decimal 29. This could indicate that tropical storms that developed near quadrature had a smaller probability of later reaching hurricane intensity than storms that formed near syzygy. The combination plot (not presented) of all 550 North Atlantic tropical storms in figure 5 repeats the maxima for each category and has little character of its own.

Northwest Pacific tropical storms were analyzed similarly to those in the North Atlantic. This analysis (not presented here) indicated that the first harmonic accounted for less than 25 percent in both categories, and other harmonics were also rather small. Rather than pointing out absence of lunar tidal influences in this ocean, we prefer to believe that the combination of a much larger area and inadequate tropical storm formation data (especially for nonintensifying tropical storms) precludes any hope of significant results in the northwest Pacific, for the earlier years in particular.

Severe Storms and Corresponding Tropical Storm Results

The north and south Indian Oceans are regions with relatively poor-quality data. Nevertheless, there is evidence of some weak relations between the synodic half month and storm formation. We found (not shown) that first-formation dates of 144 severe tropical storms in the Bay of Bengal and Arabian Sea from 1891 to 1960 occurred more frequently somewhat after quadrature, with a minor maximum after syzygy. The first harmonic accounts for 27 percent of the variance and has its maximum at decimal 32 while the rather large second harmonic of 55 percent has maxima at decimals 08 and 33. In the southwest Indian Ocean, the 48 percent of the variance explained by the first harmonic peaks at decimal 11 for 229 severe tropical storms that formed between 1911 and 1965. The second harmonic is fairly small. This may indicate a consistent tendency for severe storms during these years to occur more often about 3 days after syzygy and quadrature. That is, severe storms in the north and south Indian Ocean tend to form at the same times of the lunar month, but these differ from the formation time of hurricanes and typhoons.

The earlier moderate tropical storm stage of these severe storms was not tabulated in the southwest Indian Ocean because of data limitations (sec. 2). There was no relationship between synodic month and 127 nonintensifying moderate tropical storms that formed in the southwest Indian Ocean between 1911 and 1961.

However, the 244 moderate tropical storms that formed in the Bay of Bengal and Arabian Sea between 1891 and 1960, but did not later become severe storms, tended to form somewhat after quadrature. The first harmonic is a maximum at decimal 32 (just as severe storms in the north Indian Ocean discussed above) and accounts for 70 percent of the variance. Those tropical storms in the Bay of Bengal and Arabian Sea that did not intensify later also formed near quadrature, although the peak explains less variance. In general agreement with our findings, Visvanathan (1966) showed that, for the Bay of Bengal and Arabian Sea, tropical depressions from 1877 to 1960 that formed between 19° and 22°N also tended to form somewhat after quadrature.

Other Tropical Storm Results

This section deals with tropical storms in the northeast and southwest Pacific Oceans. For 195 tropical storms in the northeast Pacific between 1895 and 1967, the first harmonic is small, while the second harmonic of 63 percent of the variance has maxima at decimals 29 and 04. The maximum frequency is shortly after syzygy with a secondary peak near quadrature. The latter could be interpreted as the same maximum that we found for North Atlantic and North Indian Ocean tropical storms that did not later intensify into hurricanes or severe storms. The 148 tropical storms that formed in the southwest Pacific between 1940 and 1966 do not show much pattern with respect to the lunar synodic month. Our opinion that large data samples of good quality are necessary to show the small lunar effect seems applicable here again.

5. RELATIONSHIPS BETWEEN HURRICANE FORMATION AND LUNAR ANOMALISTIC MONTH

The lunar anomalistic month (27.55 days) differs sufficiently from the synodic month (29.53 days) that extremes of both cycles are not usually coincident. To look for effects of the apogee–perigee cycle, we performed the most obvious analysis by recording the Greenwich noon anomalistic decimal of the same 1,013 hurricanes and typhoons analyzed for the synodic cycle, then plotted the formation frequency, and smoothed as before (except no overlapping). However, the minor peaks on the resulting curve were not all due to variations in storm formation. The lunar orbit is an ellipse and the moon spends more time at apogee, hence anomalistic decimals at apogee last longer than other decimals. Thus, the probability is somewhat higher that storms will form during decimals near apogee. To avoid this problem, we plotted formation dates in terms of elapsed days after perigee, then made a 2-day running average. No specific time during the anomalistic month had a markedly greater storm formation frequency. However, Bradley (1964) maintained some dependency on the anomalistic cycle (for North Atlantic hurricanes only) after a correction for ellipticity was made.

It should be apparent that the anomalistic period of the lunar tide varies more slowly than the synodic because there is only one maximum (apogee) and one minimum (perigee) in 27.55 days, compared to two of each for the synodic month. To understand the ways in which these two cycles interact, we will consider some hypothetical combinations of these cycles. Then a more complex analysis of the storm dates will be discussed in view of these calculations.

Methods for theoretical calculations of the lunar-solar tidal amplitude are outlined by Schureman (1941) specifically for prediction of the ocean tide. We have included all important effects of the mass, orbits, and eccentricities of the sun, moon, and earth. Units of the calculation are 10^{-6} times the mean acceleration of gravity at the earth's surface. We present a series of four calculations in figure 6 The first calculation begins at the absolute maximum possible lunar-solar tide that can occur on the earth. Interestingly enough, de Rop (1971) has determined that this double coincidence actually occurs with a period of about 1,800 yr. In the top curve of figure 6, we see that the maximum tidal amplitude is at noon of day 1 when new moon (NM), lunar perigee (LP), and solar perigee (SP) all occur together. (The scale appears at the upper left for this calculation.) Actually, this can only occur at a specific time, because solar perigee is in late December. Then new moon and lunar perigee are occurring simultaneously at local noon somewhere around the world near 23°S. The maximum hourly tidal value on subsequent days is plotted out to 90 days after day 1. The times of new and full moon are indicated across the top of figure 6, as well as by vertical lines. The exact times of lunar perigee or apogee are indicated on the bottom. These are all calculated for that point on the earth where the new moon-lunar perigee-solar perigee situation originally occurred. At noon of day 1, the tide is all vertical, but subsequently there is included a smaller horizontal component due to motions off the plane of the ecliptic.

Other hypothetical combinations are shown by the lower three curves of figure 6. These three all begin at full moon; hence, note the reversal of scales between full and new moon from the top curve. Of particular interest is the result from the second curve (FM–LP–SP) where all conditions are the same as in the first calculation except

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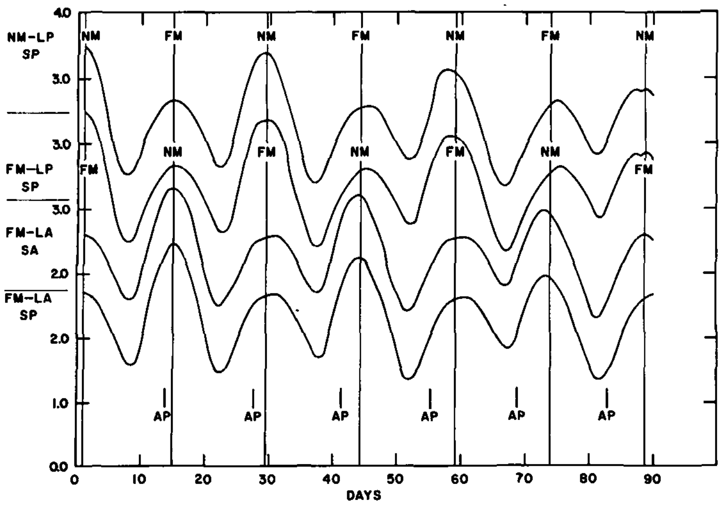

FIGURE 6.—Theoretical calculation of the amplitude of the maximum hourly lunar-solar tide each day, beginning at day 1, and carried out for 90 days after day 1. NM is new moon, FM is full moon, LP is lunar perigee, SA is solar apogee, etc. Tide is calculated at location of syzygy on day 1. Times of new and full moon for top curve are indicated across top and by vertical lines. Phases for lower three curves are reversed from top set and are shown lower along the vertical lines. Exact times of lunar apogee or perigee are indicated at the bottom by AP.

that full moon is at the start rather than new moon. We see the peculiar feature that the maximum hourly tide on full moon days throughout the 90-day period is *stronger* than on new moon days. That is, the anomalistic cycle is affecting the *magnitude* of the tide and making the normally weaker effect at full moon stronger than at new moon under these exceptional conditions. We should then anticipate that, for full moon and lunar apogee at day 1 shown in the third curve from the top, tidal amplitudes at new moon are much stronger than at full moon. The bottom curve shows little difference between tidal magnitudes with solar apogee and solar perigee at day 1. Thus, we conclude that the lunar synodic month accounts for the *timing* of the tidal maxima, while the lunar anomalistic month affects the *magnitude* strongly.

Relevant to our hurricane formation results is the obvious fact that the new–full moon cycle largely dominates the timing of the maxima and minima in the gravitational tide under all conditions. Magnitudes change and trends vary, but the extrema in figure 6 are fixed to the synodic cycle's extrema in most cases.

Now, let us try to separate the synodic and anomalistic components to see if the results of this theoretical calculation can be applied. The 1,013 hurricanes and typhoons in figure 4 were again plotted according to the synodic month but were divided into four classes depending on their anomalistic decimal. In this way, the aforementioned bias in the anomalistic cycle due to the lunar elliptical orbit is eliminated. Physically, this method is an improvement over isolating the anomalistic cycle alone since we have just seen how closely the synodic and anomalistic months can interact.

We found that for the 243 storms that formed near perigee (anomalistic decimal 00–11 and 88–99), more storms formed at and a few days after syzygy, and fewer formed at and after quadrature. That is, the curve (not reproduced) resembles upper figure 4, in general. The 261 storms forming near apogee (anomalistic decimal 37–61) also followed a very similar pattern. This is consistent, because the anomalistic component is rather steady from day to day for all of these storms, and the frequencies basically follow the synodic cycle alone. However, there is no discernible pattern when we isolate the storms that formed when the anomalistic component was increasing (anomalistic decimal 62–87) or decreasing (12–36). We can only conclude that the relation is very subtle or nonexistent, or that more data are needed. A more complex stratification may be useful, but it is quite clear from both physical and statistical arguments in this section that the synodic cycle dominates any lunar relation to the timing of storm formation, with only a minor effect from the anomalistic component.

6. FURTHER STUDIES

Another period of the moon's astronomy to be considered is the nodical month cycle (27.21 days). The lunar-solar tide is greatest when both the sun and moon pass over a given point on the earth simultaneously. The latitude of this maximum is determined mostly by the plane of the ecliptic (containing the earth and sun) and is modified slightly by the moon's position. Since the moon is always within 5° of latitude above or below the plane of the ecliptic and crosses the plane twice within the nodical cycle, we ignored this comparatively small lunar departure from the subsolar point's latitude.

Having omitted this small lunar effect on latitude, we determined whether there is a solar tidal effect on the latitude of storm formation. We found two locations for each of the 1,013 hurricanes and typhoons shown in figure 4. One is the latitude where hurricane formation was observed; the other is the absolute value of the latitude of the subsolar point on that date. Absolute magnitude is appropriate because the largest daily tidal maximum is located at the sun's latitude, but a secondary maximum (slightly smaller) is centered at the same latitude in the opposite hemisphere (Brier 1968). On June 21, the subsolar point is 23.5°N; on September 21, it is at the equator, and so on. By subtracting the absolute value of the solar latitude from the storm's latitude at formation, we may seek a component of storm formation due to changes in the latitude of the sun. Note that there are other annual variations, such as movement of the equatorial trough, that are not included here.

We found that more storms formed 8° to the north of the sun's latitude than anywhere else, undoubtedly because all storm data are from the Northern Hemisphere and storms cannot easily form near the Equator. We also separated the storms into five categories of latitude and plotted them against the phase. In general, storms located near the latitude of the subsolar point at formation time were most dependent on lunar phase. Storms in other locations tended to develop at any time during the lunar month. This result leads to the summary that the timing

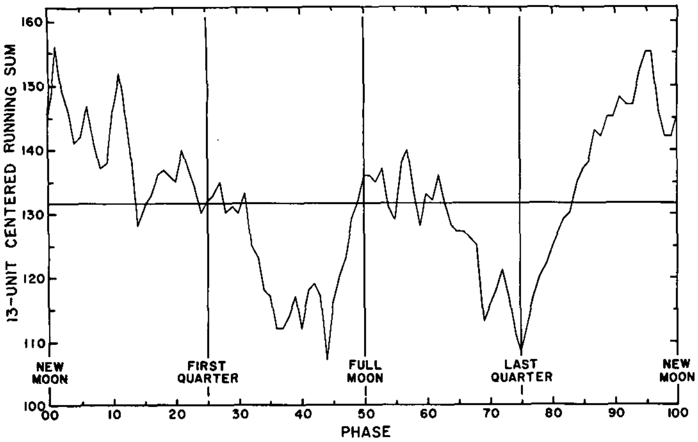

FIGURE 7.—Combined formation frequency of the same 1,013 storms with smoothing as in figure 4 (upper panel) but without overlapping.

and location are important in determining intensification, whereas magnitude is not. Note that Bradley (1964) did not detect any marked latitude effects for North Atlantic hurricanes.

The difference between storm formation at full and new moon is presented in figure 7. The formation frequency of the same 1,013 hurricanes and typhoons is plotted for decimals 00–99 without overlapping but still with a 13-unit centered running sum. The time of new moon accounted for many more storm intensifications than full moon; the minima at last quarter and after first quarter are also rather marked. The increase from last quarter to new moon is quite large. Bradley (1964), with a subset of this data, found a similar broad maximum near new moon and a lesser peak just after full moon. By contrast, Bradley et al. (1962) and Adderley and Bowen (1962) showed that rainfall is more frequent and heavier after full moon rather than new moon. Visvanathan (1966) studied the difference between new moon and full moon for Bay of Bengal and Arabian Sea tropical depressions and found a preference for depression formation at first quarter with a smaller peak near last quarter. Thus, each phenomenon presents one large peak and a smaller one during the full synodic month, but agreement among them is poor.

7. CONCLUSIONS AND SUMMARY

The following may be concluded from the present study:

1. Hurricane formation has been more frequent near syzygy than at quadrature over a period of 78 yr in the North Atlantic and northwest Pacific Oceans where formation dates are considered to be the best-documented in the world. Analysis of variance indicates a significance level of 7 percent on the unsmoothed hurricane and typhoon dates in these areas when related to the period of the half-synodic month. Additionally, a correlation coefficient of 0.87 was found between the same dates (after smoothing was performed) and this lunar cycle. This result generally agrees with correlations achieved in other studies of other meteorological phenomena related to lunar tides and indicates that a real relation between the two features may exist.

2. Severe tropical storms in the southwest Indian Ocean and Bay of Bengal and Arabian Sea over 75 yr have developed more frequently several days after syzygy and to a lesser extent a few days after quadrature. However, the reality of this finding is tempered due to limitations in available data.

3. Worldwide relations between tropical storm formation and the lunar synodic month often were not found, probably due to inaccurate data. However, for some specific oceanic regions, we showed that storms developing near quadrature intensified into hurricanes and severe tropical storms less often than those tropical storms that formed during the rest of the synodic month.

4. The anomalistic month was found from theoretical calculations to change only the magnitude of the lunar-solar tide while the synodic month generally determines the timing of extremes in the tide. In accordance with this, we found that hurricane and typhoon formation dates were not particularly well correlated with the anomalistic cycle.

5. North Atlantic hurricanes and northwest Pacific typhoons located near the subsolar point at formation time tended to form near syzygy; storms in other locations were not related to the synodic month.

6. Hurricanes and typhoons showed a major peak in formation near new moon and a minor peak at full moon with minima at last quarter and several days after first quarter.

We have examined relationships between tropical disturbance formation and three aspects of the moon's astronomical motions that affect the phase and/or amplitude of the tide: the synodic, anomalistic, and tropical months. However, we discourage systematic application of these general results to a single storm, a single location, or at a single time; the observed relationships do not invariably occur to allow such an interpretation. Favorable lunar tidal factors are not a sufficient condition because there are other larger pre-existing conditions that are necessary for hurricane formation. On the other hand, because the date of attainment of hurricane or tropical storm status is probably not the most indicative feature in revealing when and how the tidal phenomena have maximum influence, we probably should also study cases of rapid intensity changes, formation in unusual locations or at unusual times, or the critical period when an ordinary disturbance acquires significant organization; such data are extremely limited at present, however. Brier and Simpson (1969) dealt at length with the relationships between large and small semidiurnal pressure variations and corresponding cloudiness and rainfall changes and suggested that lunar-solar tidal changes may play a role in these observed changes. They further suggest how the small resulting convergence field variations could become concentrated in cumuli, which in turn are a fundamental feature of tropical storms and hurricanes. It remains to be postulated what mechanism could bring about tropospheric pressure variations where lunar gravitational forces are involved.

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